Department of the Navy
Office of Naval Research
Contract Nonr-220(08)
Project NR062-166

INVESTIGATION OF THE MECHANICS OF CAVITATION AND CAVITATION DAMAGE

Final Report

Robert T. Knapp
Hydrodynamics Laboratory
California Institute of Technology

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TABLE OF CONTENTS

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INTRODUCTION

This final report covers a period of approximately four years, since this contract was initiated in March 1952. Furthermore, even at that time some of the phases of the work had already been started. In discussing the progress of these different phases, no attempt will be made to separate these initial phases from the continuation under this contract. The most important results obtained during the life of this contract have already been published in a series of technical articles.[1, 2, 3] † Therefore, in such cases only summaries will be incorporated herein. In cases in which the phases have not reached the publication stage, a more complete outline will be found.

Four phases of this investigation of cavitation will be reported, as follows:

I. Effect of Pressurization on Cavitation Properties of Water
II. Mechanics of Fixed Cavitation
III. Hydromechanics of Cavitation Damage
IV. Preliminary field tests of Intensity of Cavitation

Phase I has not been reported in the literature; II, III, and IV have been presented in the references cited.

I.

Effect of Pressurization on the Cavitation Properties of Water

A. Previous Work

The initial work on the effect of pressurization on the cavitation properties of water was carried on by Harvey in the early 1940s.[4, 5, 6] Previous to this time it had been generally assumed that cavitation occurred in a flowing liquid whenever and wherever the static pressure in the liquid was reduced to the vapor pressure. Harvey, however, as a biologist and physiologist, was acquainted with many situations in which liquids would support appreciable tension before they would rupture to

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† Numbers in parenthesis refer to references at end of report.

form a bubble, even though in many cases these liquids were not pure but were known to contain dissolved gas. During his wartime inve sti-gations of the mechanics of wound damage, he discovered that much damage was associated with the violent formation of a cavity by a high-speed missile traveling through the flesh. With his background, he was surprised that a cavity would open as soon as the vapor pressure was reached. Therefore, he started investigating the reason for the early opening of the cavity. He thus developed the concept of undissolved gas nuclei as being "weak spot" sources for cavitation. He carried on a considerable experimental investigation of the properties of water and water-like liquids. His experiments on the effect of pressurization of water were an outgrowth of his hypothesis of the presence of nuclei and were for the purpose of obtaining indirect evidence as to their existence. He reasoned that if undissolved gas nuclei reduced the effective tensile strength of water to zero, then if they could be forced to dissolve into the liquid, its tensile strength would increase. He assumed that they could be forced to dissolve by increasing the pressure on the water enough to drive them into solution. One of his difficulties was to devise methods of testing the tensile strength of the liquid after the treatment. He tried various methods of doing this, such as pulling a clean glass rod out of the pressurized liquid at high velocities to see whether or not he could induce cavities to form at the downstream end. The simplest method he used, however, was to heat the pressurized sample of liquid at atmospheric pressure until it boiled. He reasoned that the difference between the saturation pressure corresponding to this temperature and atmospheric pressure was the effective tensile strength of the sample. Some of his experiments made in this manner showed effective tensile strengths of 10 atmospheres and higher. However, these experiments were largely qualitative. The experiments carried on under this contract and which now will be discussed, had the objective of obtaining more detailed information concerning the effective tensile strength of water, using Harvey's pressurization method, with the hope of getting more quantitative information.

B. Pressurization Technique

Although several different types of experiments were carried out on the effects of pressurization, in all cases the pressurization was ap-

plied in a simple piece of apparatus, shown in Fig. 1. The high pressure is produced in the pressurizing chamber by a relatively long-stroke piston which is driven by a large-diameter, low-pressure piston fastened to its lower end. The low-pressure piston and its cylinder are a part of a closed hydraulic system which also includes a stock aircraft type gear pump with the associated control valves and reservoir. (Fig. 2) The area ratio of the two pistons is about 33:1, thus making it possible to obtain any desired pressure up to 30,000 psi (2,000 atmospheres) in the chamber with a maximum working pressure in the hydraulic system of 1,000 psi. The pressurization chamber is 2 5/8 in. in diameter and has a usable length of approximately 30 inches. This length makes it possible to determine the pressure in the treatment chamber quite accurately by measuring the increase in over-all chamber length. A dial gage is used for this purpose. One complete revolution of the dial gage corresponds to about 1,000 atmospheres pressure. The chamber is closed at the access end by a plug having an unsupported area-type seal which is simple, satisfactory, and reliable. The long length of this cylinder was needed to treat the glass working-section used for the dynamic cavitation studies described later. However, it also permitted simultaneous pressurization of a number of boiling point tubes, thus insuring identical treatment for the group.

During pressurization it was necessary to have the chamber completely filled with water. It was impossible to prevent this water from becoming contaminated with dirt, rust, etc., so that it was necessary to keep the water contained in the equipment being pressurized from coming in contact with the chamber water. However, since the pressures utilized were high enough to produce appreciable changes in volume of the liquid (maximum treatment pressure is 10 per cent of the modulus of elasticity of water), but much less change in volume of the glass containers, it was necessary to permit flow into and out of the equipment being pressurized. These conflicting requirements were satisfied by covering all openings into the glass equipment with water-filled flexible bags before putting the equipment into the pressurizing chamber.

C. Description of Experiments

Three different types of experiments were carried out to investigate various aspects of the effect of pressurization on the apparent tensile strength of water. These were (1) boiling point experiments, (2) pressure release experiments, and (3) dynamic flow experiments. They will be described separately.

1. Boiling Point Experiments. The most exhaustive of these three groups of experiments was the boiling point series. This was patterned on Harvey's work, but in general used much larger samples than he used. Basically, these are very simple experiments. A filled container of the liquid to be tested is placed in the pressurization chamber and held for a specified length of time at the desired pressure. It is then removed and heated at atmospheric pressure until boiling occurs. Under these conditions the beginning of boiling is very simple to detect since the first bubble grows very rapidly and becomes large enough to force an appreciable fraction of the liquid out of the container. This is due to the fact that after pressurization the boiling point is above saturation temperature at atmospheric pressure. Therefore, once a free surface is created by the formation of a bubble, there is enough sensible heat available in the surrounding liquid to cause the bubble to grow rapidly. In planning the initial experiments it was felt that this growth might be violent; therefore, the heating was performed behind a suitable transparent screen. However, in several hundred experiments, there were only a few cases in which the vaporization rate was fast enough to break the container, and in these cases rupture was not very violent.

(a) Determination of Boiling Temperature. The chief difficulty involved in making these measurements is the determination of the temperature of the liquid at the instant of boiling. Unfortunately, it is extremely difficult to measure this directly. In order to eliminate occluded gas on the surface, any temperature-measuring device must be cleaned and pressurized with the sample. Normal mercury-filled thermometers are unsatisfactory, both because they will not stand the required pressures and because of their long time-lag. Wire thermocouples could not be used because it was found to be practically impossible to clean metal surfaces well enough to eliminate all gas from surface irregularities, and

the pressurizing treatment did not prove adequate to force this type of nucleus into solution. To avoid these difficulties, two techniques were used. The first was to heat in a circulating liquid bath, with a low enough heating rate so that the difference between the bath and sample temperatures was negligible. The second method consisted in heating the tube at a constant rate by an external coil of resistance wire having a controlled electrical input. This was shielded from air currents or other influences which might change the rate of heat loss from the system. The rate of heat rise was determined by thermocouples in unpressurized samples. The upper limit of these measurements was, of course, the normal boiling point of water at atmospheric pressure. The water was then replaced by a high boiling-point, low-viscosity liquid, and measurements were continued up to the maximum temperatures anticipated for the tests. The rate of heating in the latter tests was greater for the same heat input because of the lower specific heat of the liquid used. These rates were corrected to the equivalent water heating rate by the use of the ratio of the specific heats. With this heating curve the experimental determination of the boiling point reduced itself to the measurement of the time required to heat the sample to boiling.

(b) Sample Containers and Cleaning Techniques. One of the basic purposes of this group of investigations was to study the initiation of a cavity in a liquid. In many ways it would be desirable to study this problem in the interior of a large body of liquid so that the entire phenomenon would not be affected by the walls of the container. However, one possible hypothesis is that under all normal conditions, cavities originate on the walls of the container. This viewpoint assumes that even in untreated water the effective tensile strength of the liquid is greater than the adhesive forces of the liquid to the container. This is known to be true in many cases. Harvey found that experiments made in metal containers always showed low boiling points, with the vapor bubbles originating on the walls, presumably because the metallic surfaces could not be cleaned sufficiently well to eliminate all gas pockets or occluded gas film. As indicated in the last paragraph, wire thermocouples were eliminated from the experiments for this reason. Harvey's measurements with clean glass containers showed much higher effective tensile strength,

but it was not completely clear whether in these cases cavities always originated on the walls or whether in some experiments they originated in the body of the liquid. Blake and others[7,8,9] and[10] had produced cavities in the interior of the liquid by concentrating the energy from a series of high frequency transducers, but the liquid in this experiment, although it had been treated to remove as much air as possible, had not been pressurized and thus might have contained reasonably large sized gas nuclei.

For these reasons, the cleaning and filling of the containers was one of the most important items for study. It developed that the major fraction of the time and energy that went into these experiments was used to perfect filling, cleaning, and pressurizing techniques to minimize uncertainties in the interpretation of the results. It is inevitable, therefore, that these factors monopolize a large part of the discussion.

(c) Glass Crucible Experiments. The first set of boiling point experiments was made with 50 c.c. "VYKOR" glass crucibles as sample containers. This particular shape was chosen because it offered a large release surface and thus presumably would prevent any possible explosion due to a violent evolution of vapor from a liquid sample that had reached a relatively high superheat. In the initial experiments, these crucibles were cleaned with synthetic detergent before each test, and placed, while still wet, in a basin of the water to be tested. While beneath the surface, they were covered with a diaphragm of thin rubber (toy balloon) which had been previously cleaned with detergent. This was fastened to the crucible by rubber bands. Care was taken to see that no bubbles were trapped in the container. The crucibles were then pressurized. A circulating glycol bath was constructed to heat the specimens to boiling point. The test procedure was to remove the rubber cover, place the crucible immediately in the glycol bath, and then measure the time it required for the sample to boil. The boiling points measured in this first series were low, averaging about 216°F. The reference temperature was taken as 211°F, which is the saturation temperature of water at the elevation of Pasadena. The maximum boiling point observed was 255°.

The scatter in the measurements was thought to be quite high; it was felt that part of it might be due to faulty cleaning techniques. Hot dichromic acid was therefore substituted for the detergent as the clean-

ing agent. Under these conditions, the average boiling point was observed to be 220°F. This increase of 4 degrees was not considered very significant as compared to the observed scatter.

Several characteristics of these tests were observed, which indicated that changes in technique were necessary. At sample temperatures above 211° F, evaporation from the free surface was relatively rapid. The loss of liquid was great enough to raise questions concerning the validity of the calibrated heating rate since that had been determined with a full crucible. Those samples which boiled at 230° F and above, showed no visible bubble formation until boiling, which occurred with a severe "bumping" action. This was violent enough to throw most of the sample out of the crucible. Careful observation of the test indicated that in many cases boiling was triggered by the arrival of an external contaminant, probably a dust particle, from the air. Attempt was made to improve the technique by using clean watch glasses as crucible covers. These were put in place before the sample was pressurized, and were left in place during the heating. Since they were not fastened, they did not affect the pressure during the test. It was hoped that they would have two beneficial effects: - prevent contamination from the atmosphere, and reduce the rate of evaporation by eliminating most of the free surface. Using this technique, the average boiling point increased to about 230° F, with one sample showing a maximum of 270° F. However, it was observed that during heating, evaporation began at the contact line between the crucible and the cover and proceeded quite rapidly so that vapor space soon formed. Since this glass cover was not heated, it acted as a condensing surface and soon droplets were observed to form on its undersurface. Cases were observed in which boiling was obviously initiated by the fall of one of these droplets from the surface of the watch glass into the liquid below. This series of experiments had several interesting results: (1) Tests made with unpressurized water but with the cleaning techniques just described, boiled when saturation temperature was reached; (2) pressurized samples required, with few exceptions, appreciable superheats before boiling occurred, and occasionally one required as much as 50° superheat; (3) the scatter in the observed results was too great to permit the determination of the effects of varying the pressure level

or time of pressurization; (4) no difference could be observed between the behavior of tap water and distilled water; (5) even for the samples which reached the maximum superheats, boiling, although it occurred suddenly, was not violent enough to require a large free surface for release. In the most severe case, the water droplets were thrown only a few inches above the crucible; (6) the presence of a large free surface with or without a loose glass cover, introduced many side effects, which obscured the main phenomenon.

(d) Experiments with Open Test Tubes. In this series of experiments standard pyrex test tubes 18 mm in diameter, 150 mm long, were substituted for the glass crucibles in order to reduce the relative amount of free surface. Since the glycol bath was not easily adapted for the use of this shape of tube, it was abandoned in favor of the direct heating coil described in paragraph (b). The first material used for closure during pressurization was dental rubber dam, which was found to have less surface impurity, (talc, etc.) than the material previously employed. Also it appeared somewhat more hydrophilic. It was carefully cleaned and kept immersed until needed. In the initial boiling point determinations, the dam was removed just before heating commenced. However, it was again found that contamination from the atmosphere occurs very rapidly. It was therefore decided to leave the rubber closure in place during tests. It was felt that this would not affect the boiling point measurements since in making the closure the rubber was not under stress; hence, it could exert no pressure on the water until an appreciable volume change had occurred. In addition, some simple experiments showed that the maximum pressure which it would sustain was approximately 1 psi.

The series of boiling point determinations made with the dam in place showed an average boiling temperature of about 260° F. One sample, however, reached a temperature of 332° F before boiling, which corresponds to a tension of approximately 185 psi. Two types of boiling were observed. With the high temperature samples, boiling appeared as a minor explosion, which ripped the cover from the top of the tube. In the samples which showed lower boiling points, the first bubbles were observed in the top section of the tube. The boiling action subsequently worked down to the bottom, taking approximately one second to do so.

As the number of tests increased, different variations of this latter type of boiling were observed, all of which had the common characteristic that the initial bubbles formed towards the top of the tube, near the rubber cover. It was finally concluded that the rubber surface was a sufficient source of contamination to mask the properties of the liquid. In an attempt to remedy this difficulty, a small series of tests was made using dialyzing cellophane as the closure in place of the rubber dam. This material is very hydrophilic and easier to clean. Although conditions were somewhat more satisfactory, the contact area between the closure and the glass tube still seemed to be a source of contamination. Furthermore, the maximum boiling points obtained in these series approached the useful working limit of both the rubber and cellophane closures. Hence, it was decided to try an all-glass test chamber even though this would require a more involved cleaning and filling technique.

These series of experiments with open tubes emphasize the following facts:

1. The contact surface between the container and the liquid was always a potential source of weakness, and unless very careful cleaning techniques were used, unsatisfactory results were obtained.

2. Even with the best techniques thus far developed, there was a wide scatter in results, which pointed to the tentative conclusion that this might be a characteristic property of the water itself;

3. Unpressurized samples in clean tubes showed superheats from 1° to 4°, but no higher. Explosive type boiling was not observed. Vapor bubbles were seen to form within the body of the liquid as well as on the walls. In general, the characteristics of these unpressurized samples were the same as those of parallel tests in the crucibles.

4. In contrast to this lack of sensitivity of the unpressurized samples to changes in test crucibles, the pressurized samples showed progressive increase both in average and in maximum boiling points with each improvement in cleaning or protecting techniques.

(e) Experiments with Closed Test Tubes. The final type of test chamber used in this investigation was a simple adaptation of the standard pyrex test tube used in the previous set of experiments. This tube is 18 mm in diameter and 150 mm long, and holds 30 cc. Hemispherical glass domes were welded to the top of these test tubes to permit cleaning and filling. Glass capillaries were welded to these domes. Figure 3 shows two types, one with a single capillary tube, and one with two parallel capillaries. These capillaries were about 1 1/2 in. long and a relatively large bore. It was anticipated that the two-capillary dome would be easier to clean, but it was found that equally good results could be obtained with a single capillary. Therefore, it was adopted as standard. Several different cleaning techniques were investigated. One that produced some of the most consistent results was the use of vapor pressure to force the cleaning solution, rinse water, and test water in and out of the tubes. In this technique, a small amount of water was injected into the tube and boiled to drive out air. The tube was then inverted so that the vapor pressure could drive out the remaining liquid. As the last of the liquid left the tube, the tip of the capillary was immersed in the next liquid with which it was desired to fill the tube. This would be drawn in as the tube cooled. By a series of such alternate heatings and coolings, the chromic acid bath could be forced in and out, the tube rinsed with clean water, and when all of the traces of the acid had been removed, the tube could be finally filled with the water to be tested. Some of the highest superheats measured were obtained with tubes cleaned in this manner. Detergent solution could be employed, using the same technique. However, it was felt that this technique might remove an appreciable amount of the dissolved and undissolved air in the final sample and thus change its characteristics. Therefore, two additional methods of cleaning were investigated. The first employed stainless steel hypodermic

needles small enough to pass through the capillary tubing. The second substituted polystyrene hypodermic tubing in place of the stainless steel hypodermic needles. Meticulous techniques of using either the needle or hypodermic tubing were found necessary to prevent contamination of the test chamber capillaries. Such contamination caused premature boiling in the capillary tube. Again, the most satisfactory results were obtained when the entire cleaning operation was carried out with the tube submerged so that no air came in contact with any part of the critical glass-water interface after cleaning commenced.

At first these capillary-top test chambers were pressurized by enclosing them in dialyzing cellophane tubing, which was completely filled with test water. A much simpler protection technique was discovered, which consisted of connecting two of these tubes, while still submerged, with a short length of carefully cleaned latex rubber hose. The length of this hose was chosen so that the volume of water contained in it would more than compensate for the compression of the water in the glass test chambers during pressurization.

After these cleaning and pressurizing techniques had been perfected, several different series of tests were made to explore such variables as level of pressurization, duration of pressurization, time between pressurization and testing, and rate of heating. Typical results are shown in Figs. 4 to 6. It will be noted that even with all of the care that had been expended in developing consistent cleaning and pressurizing techniques, these series continued to show wide scatter in the results.

The tubes were always kept under close observation throughout the heating period in an attempt to determine the point of origin of the bubble. This was very difficult because of the uncertainty as to when the sample would boil, and because, once boiling was initiated, the action was very rapid. However, it was concluded that often the first bubble formed on the glass wall. This is to be expected since part of the heat is transmitted by conduction through the wall to the water, and hence, the wall must be somewhat hotter. Nevertheless, an alternate explanation could be that the main effect of the pressurizing treatment was to eliminate weak spots on the wall that might otherwise initiate boiling, and that the body of the liquid was inherently of high tensile strength and unaffected by the pressurizing treatment. Consequently, two additional groups of runs were

made to check this point. In both groups the tubes were cleaned and pressurized as before. The pressurized water was replaced by normal, unpressurized water, after which the boiling point was determined. In the first group of tests the substitution was made by heating the pressurized tube until boiling did occur, continuing the heating until all of the pressurized water was driven out, and at the last moment immersing the capillary in unpressurized water which was then drawn in to fill the tube. In the second group of tests a substitution technique was developed, which did not require the boiling of the pressurized liquid. A modified design of the two-capillary dome tube was used, with one capillary extending a short distance into the body of the tube. The tubes were cleaned and pressurized in the standard manner. They were then submerged in unpressurized water and suction applied to the short capillary. The flow induced in this manner flushed out the pressurized water, replacing it with untreated liquid. Circulation was continued until it was sure that the exchange had approached completion. The tubes were then immediately heated and the boiling point determined. Proof runs were first made on these modified tubes by following the normal procedure of determining the boiling point of pressurized water. Since boiling points of 350° F were obtained, it was concluded that this modification had not affected the tube characteristics. These two groups of tests with unpressurized water in pressurized tubes showed the same results: Boiling occurred within a few degrees of saturation temperature, small air bubbles became visible and rose through the water even at lower temperatures. There was no significant difference between the results of these two groups and that of a previous group in which the tubes were cleaned and filled in the normal manner, following which the boiling point was determined without any pressure treatment. A comparison of the boiling point obtained in these three groups with those determined after pressurization treatment of the liquid shows conclusively that the untreated water does not have the high tensile strength, and that the pressurization treatment affects the liquid itself as well as the liquid-glass interface.

One other set of exploratory experiments was performed, using carbonated water. The technique was not so simple as with uncharged water, since during the filling process bubbles were formed at the slightest disturbance. However, it proved possible to fill and pressurize a few tubes with little gas loss. The temperature at which gas bubbles first appeared indicated effective tensile strengths of the mixture of the same order of magnitude as those found with pressurized plain water. The major visible difference was that with the carbon dioxide, bubble growth, after it once began, proceeded at a slower rate than that of the vapor bubbles. This was apparently due to the fact that the rate of bubble growth was partially dependent upon the rate at which the carbon dioxide could diffuse through the water and reach the interface.

2. Pressure Release Experiments. Several features of the boiling point experiments were felt not to be completely satisfactory. One of these was the rigid boundary inherent in the use of a glass test chamber. Another was the necessity of having a free surface, even though small, to establish the pressure at which the boiling point was determined. The third was the indirect measurement of temperature at the instant of boiling, that is, its inference from the rate of heating. It was, therefore, decided to try a new type of experiment: to heat the sample to a given known temperature, maintaining the ambient pressure at all times at or above the increasing saturation pressure of the heating sample, and after the desired test pressure and temperature had been obtained, to determine the effective tensile strength of the liquid by reducing the test chamber pressure until vapor bubbles formed. The corresponding pressure drop from the maximum saturation pressure would be a measure of the effective tensile strength. It was planned to make this pressure release at a sufficiently rapid rate to prevent any appreciable heat loss from the sample during the test. This would insure that the change in sample temperature would be very small in comparison to the drop in saturation temperature during the pressure release. It was believed that with this type of a pressure chamber, a bag of dialyzing cellophane could be used to hold the sample, since it would have no rigid walls, and hence would require no free interface to insure equilibrium of pressure between the sample

and the surrounding gas. Another advantage would be that the maximum time required for the test could be predetermined, since the rate of pressure reduction could be controlled arbitrarily. With moderately high release rates, test times could be short enough so that a complete motion picture record could be made at 64 frames per second or faster, and thus obtain accurate information concerning the point of origin of the initial vapor bubbles.

Figure 7 shows the appearance of the pressure release chamber. The two opposite faces were made of heavy plate glass, sealed with special high temperature O-rings in the stainless steel body. The operating technique was as follows: The sample was suspended in the center of the chamber. A small amount of water was then added and the chamber closed. The chamber was then heated by resistance coils in the four stainless steel sides. Since the free water in the chamber was in direct contact with the metal sides, its temperature was always higher than the sample until equilibrium conditions were reached. Therefore, it vaporized and maintained the chamber at the saturation pressure corresponding to the temperature of the walls. At the beginning of the heating process, the control valve was left open until all of the air was forced out by steam. Heating was relatively slow due to the large mass of the pressure chamber. After the desired temperature had been reached, it was held constant for a soaking period to insure that the temperature of the sample had reached equilibrium with that of the surrounding vapor.

The actual test then consisted in releasing the pressure in the chamber, and observing its value at the instant at which a bubble formed in the sample. The decrease in pressure was taken as the measure of the tension in the liquid. Two rates of pressure release were used. The fast rate was approximately 30 psi per second. In these tests the observations were made with the motion picture camera, whose field of view included both the sample and the pressure gage. In the slow release, the rate of pressure drop was from 1 to 5 psi per second. Here the camera was not needed, since sufficient accuracy could be obtained by the two observers, one watching the sample and the other the pressure gage.

(a) Cellophane Containers. No satisfactory results were obtained with cellophane containers since it was found that their tensile strength decreased so rapidly as heating progressed that they could not hold the weight of the contained water under the desired test conditions. Since no other flexible sheet-type of material was found that was both hydrophilic and strong enough, this approach was abandoned.

(b) Closed Test Tubes. A rather extensive series of experiments was carried on in the pressure release chamber using the closed top test tubes developed for the heating experiments. Most of these had single capillary tops, although some measurements were made with the double capillary tops. Most of the experiments described under the boiling point tests were repeated in the pressure release chamber. In general, the results obtained from all tests with pressurized samples paralleled those made by the heating method. However, the tests made with unpressurized samples showed rather unexpected results. These tests were all made with cleaned tubes. In one group the tubes were cleaned, filled, and tested without pressurizing. In the second group the tubes were cleaned, filled, and pressurized, after which the pressurized water was flushed out and replaced with unpressurized water. The test results from these two groups were similar to those from the corresponding groups which were tested for boiling point in that there was no significant difference between the groups. However, both groups tested in the pressure release chamber showed surprisingly high effective tensile strengths as compared to the similar groups tested by the boiling point method. For example, one sample from the flushed group showed an effective tensile strength of 275 psi. The highest value shown in the group whose only treatment was cleaning, was 230 psi. Both of these effective tensions are higher than the average of the pressurized samples, although many of the individual tests in the latter group showed much higher values, the maximum tension measured by this method being 420 psi. The average tension exhibited by 19 samples tested in cleaned unpressurized tubes was 113 psi. However, these can be separated into three groups according to the maximum pressure, p_v, in the chamber at the beginning of test. The lowest group was composed of three samples which were tested with a p_v of

120 psi or less. The average tension of these samples was 22 psi. The chamber pressure for the second group was 200 to 250 psi. The twelve tubes in this group showed an average tension of 128 psi. Four tubes were tested in the third group. Here p_v was between 300 and 400 psi. The average tension measured for this group was 136 psi. It is significant that the effective tensile strengths of the samples increased with the chamber pressure. This leads to the conclusion that the pressure release technique inherently includes a low level pressurization which increases the effective tensile strength. The fact that this pressurization is carried on at an elevated temperature probably assists in the process. This behavior might have been predicted from the boiling point experiments because these showed that even low values of pressurization increased the effective tensile strength of the water.

The results from the two methods of testing permit one further conjecture. The average of the tests of unpressurized water in clean test tubes showed an effective tension of 1 to 1 1/2 psi. However, individual samples gave values as high as 47 psi effective tension. The 22 psi average tension of the group tested in the pressure chamber at p_v 120 psi, or lower, is well within this spread. This implies that the tension shown in the boiling point tests of the unpressurized samples may have been due to pressurization in the city water mains, since the water used in the laboratory has been pressurized for an indefinite time at approximately 100 psi.

Test of Pressurized Samples. Figure 8 is a plot of all of the tests made with the standard sized capillary-top test tubes, using pressurized samples. The level of pressurization varied from 5,000 to 15,000 psi, and the time from 15 minutes to several hours. These differences in the pressurization treatment are not considered important since the boiling point tests described previously showed no significant effects of variations within these limits. The two pressure release rates are indicated by the two symbols, the circles being for the slow release rate, and the crosses for the fast. The 45° lines show the maximum tension that could be applied to a sample tested at a given chamber pressure. Points falling on this line indicate that these samples did not boil even when the test pressure fell to atmospheric. In a few of these samples subsequent boiling was produced by rapping the chamber sharply after the pressure release had been completed.

Several conclusions may be based on these results:

(1) The release rate appears to have little effect upon the tension at which boiling occurs. This is contrary to the original expectations, as it was assumed that the slow release rate would be a more severe test.

(2) The scatter in the results is similar to that of the boiling point tests.

(3) The average effective tension seems to increase somewhat with the initial test chamber pressure. This implies that the low level, high temperature pressurization of the sample during the heating of the pressure chamber to the equilibrium test pressure added to the effectiveness of the original high level cold pressurization.

It was anticipated that the pressure release experiments would reduce the scatter in the results and furnish more basic information than was actually found. The fact that they did not is apparently due to the inherent characteristics in the nuclei distribution to be found in samples of this size. A comparative analysis of the pressure release methods with the boiling point method of determining effective tensile strengths shows that the conditions of testing differ quite fundamentally in ways which might be employed to advantage on work with liquids whose boiling characteristics are more closely related to the physical characteristics of the liquids themselves rather than to nuclei or similar microscopic impurities. The boiling point experiments are basically constant pressure experiments. All testing is done at a predetermined low pressure. Differences in test results are primarily differences in temperatures. The pressure release technique, on the other hand, is primarily one of constant test temperature in which a known high temperature is preselected and maintained constant while the pressure is dropped until failure occurs. Since the tensile strength of a pure liquid is a function of the difference between the test temperature and the critical temperature, these two test methods might be expected to yield different results. The fact that they do not do so in tests with water is additional experimental evidence of the fact that the true tensile strength is not the property being tested, but rather the effective tensile strength as determined by the existing nuclei.

3. Dynamic Flow Experiments. The two preceding types of experiments were both static, that is, there was no liquid motion, and tension was produced by changing either the temperature or the external pressure. It seemed desirable to study the effects of pressurization for

conditions under which cavitation is produced by pressure variations in flowing liquid. Obviously, this requires a flow circuit capable of producing negative pressures in the absence of cavitation. The obvious way of doing this is to use a nozzle and diffuser system. This would be directly comparable to a water tunnel circuit in which the minimum pressure occurs in the working section. To be a satisfactory tool, the nozzle and diffuser sections must be as carefully made as those for a water tunnel to insure that the pressure in the working section is the lowest pressure in the system. If the nozzle and transition sections are not properly made, local low pressure zones of unknown magnitude, location, and intensity may be created. Such zones, if they exist, make it impossible to calculate the effective tension at which cavitation occurs. However, if correctly designed shapes are used for the nozzle and transition section, it is possible to calculate the pressure in the working section from Bernoulli's equation, with sufficient accuracy for this type of experiment. With these factors in mind, a tentative method of approach was developed. The salient points of this method are as follows: In order to obtain results that will be comparable with the boiling point and pressure release experiments, the flow circuit, including the container for the water to be tested, the nozzle, working section, and diffuser must all be made of glass, and be of such dimensions that the same cleaning and pressurization techniques can be used in the system as were used in the other two sets of experiments. Funds were not available to construct a continuous flow circuit which could meet such rigid specifications. Therefore, it was decided to use a single-pass system in which a sample of treated water would be caused to flow through the working section under controlled conditions of pressure and velocity. Thus, a given sample of water would be tested only once, just as it was in the other two types of experiments. It was decided to make the water container, the nozzle, working section, and diffuser, from a single piece of glass tubing with dimensions small enough to fit into the existing pressurizer. Figure 9 shows a view of one of these tubes. The large cylindrical section above the nozzle is the water reservoir. The nozzle and diffuser are geometrically similar to the nozzle and diffuser of the High-Speed Water Tunnel in the Hydrodynamics Laboratory. The working section is only one diameter long instead of

four to six diameters used in the working sections of the water tunnel. The water tunnel nozzle had been carefully designed, using the method of Tsien, to have a monotonic pressure drop.

The greatest difficulty was experienced in finding a suitable method of manufacture. It was felt that it would not be satisfactory to mold the glass roughly to shape and to finish the inside to precise dimensions by grinding and lapping with formed laps, because such a method would produce a surface finish much inferior to the fire-polish finish of normal glass tubing. The minute scratches and crevices which would inevitably result from such a technique would very probably act as nuclei hosts. It was finally decided to flame-shrink pyrex tubing on a precision stainless steel mandrel. This method of manufacture was discussed with several firms in Philadelphia that were known to have developed this specialized technique of blowing and shrinking glass to precision shapes. Finally, the Schutte and Koerting Company agreed to undertake the manufacture of the tubes. The mandrel, having the form of the nozzle, working section, and diffuser, was made in the Instrument Shop of the Hydrodynamics Laboratory. Since the working section had the smallest diameter, the mandrel had to be built in two pieces with a joint in the working section so that it could be removed after the shrinking operation was complete. This joint was very carefully made so as not to leave a ridge in the glass in this critical area. In this type of apparatus the length of run is determined by the amount of liquid contained in the storage section, the cross section of the throat, and the desired velocity. For the range of conditions it was desired to explore, calculations of the run duration showed that it would vary from a fraction of a second to one second. This fact controlled the type of auxiliary equipment which had to be designed, both to drive the flow and to record the results. Figure 10 shows the operating system which was developed. D is the working chamber, which is constructed of heavy lucite. It has a square cross section with plane faces, and a circular bore. The glass "venturi tube" is placed inside this working chamber after cleaning, filling, and pressurizing. It is supported on a plaster of paris seat molded in a brass ring, which is fastened to the lucite. An individual seat is cast for each glass venturi to give uniform support and prevent the chamber from being damaged by

the sudden application of pressure at the beginning of the run. The lower end of the diffuser enters the opening into Tank F. An O-ring seal is used to prevent flow between D and F when the venturi tube is in place. After the tube is installed, the space between it and the lucite working chamber is filled with water. This eliminates most of the optical distortion due to the cylindrical bore and permits good visual and photographic observation. The chamber is sealed by the cover E, which is connected by a large hose to the air system. The main air supply from the right enters the pressure-regulating valve A. This is adjusted to provide the desired driving pressure for a given set of runs. Air reservoir B is in parallel with the main air line to permit a large volume of air flow into the working chamber D without affecting the driving pressure. C is a solenoid operated quick-opening valve which is used to start the experiment. Mercury manometer M gives an accurate reading of the drive pressure in Tank B. A small by-pass line leads from the air system to the downstream receiver R. The pressure in this receiver can be preset at any desired value through the use of this line and gage G. Receiver R can be evacuated in case a lower system pressure is desired. The volume of R is about fifty times that of the water sample to be tested. Therefore, it can be assumed that the receiver pressure is constant during the entire run. Likewise, air reservoir B holds about forty times the water volume, and the flow velocities in the supply line to D are too low to have significant friction loss. It should be noted that filling the space between the venturi tube and the test chamber D with water not only corrects the optical distortion, but also reduces the initial flow required to bring the system up to working pressure when the valve C is opened.

This scheme of operation makes it feasible to set and record all the quantities that control the flow before the run is started. The only determination that has to be made during the run is the behavior of the liquid in the working section. This is recorded photographically with a high-speed motion picture camera, using an Edgerton flash lamp as the source of illumination. A standard repetition rate of 1,000 per second was used in making these photographs. It is possible to take 2,000 frames in a single run, that is, a continuous record can be made for two seconds. This is longer than was required for any of these tests. The photographic record is used for two purposes, (a) to determine if, where, and when cavitation

occurs; and (b) to determine the position of the water surface in the reservoir portion of the glass venturi tube. Since the diameter of this portion of the tube is constant and known, and since the repetition rate is accurate to a small fraction of a per cent, this measurement determines the rate of flow of the liquid through the working section. An examination of the record showed that this was not as simple as it was hoped, because under the transient flow conditions the liquid surface did not remain flat but became approximately parabolic. However, the surface reached an equilibrium configuration comparatively early in the run. Steady state measurements were made of the flow characteristics of the tubes, including the determination of the recovery efficiency of the diffuser. It was therefore possible to obtain two independent estimates of the pressure and velocity in the working section by flow calculations based either on the pressures existing at the upstream or the downstream end of the tube. These two independent methods proved mutually consistent.

Since the tubes were so large, it was very difficult to use as rigorous a cleaning technique as that employed for the closed top test tubes used in the boiling point and pressure release experiments. However, as far as possible, the techniques were parallel. The venturi was cleaned by soaking in a concentric dichromic acid solution, then rinsing in a stream of cold tap water. It was immediately immersed, while still very wet, in a stainless steel trough filled with the sample water. Both ends were then covered with dialyzing cellophane sheet fastened with rubber bands. These sheets were sufficiently strong so that the tube could then be handled in air and transferred to the pressurizing cylinder. In general, the tube was pressurized for one hour at 30,000 pounds psi. It was hoped that this higher pressure level would tend to eliminate the effects of any dust particles that might have settled on the wet surface during the time of transfer of tube from the water rinse to the filling trough.

Although the cellophane closures were strong enough to permit handling the filled tubes in air, there was only a small margin of safety. Therefore, they could be depended upon to break in the working chamber as soon as the driving air pressure was applied. In nearly all cases, the lower seal broke so as to give a clear opening for the discharge of the water.

The break at the upstream end was usually not so satisfactory, probably because it carried no initial water load. Although this break always provided more than enough area to eliminate pressure drop across it, the uneven tear often produced enough asymmetry of the air flow to result in a disturbed water surface in the storage section. This increased the difficulty of calculating the rate of flow from the photographic measurements.

The most consistent set of results obtained with the pressurized flow tubes was carried out at an air drive pressure of 9 psig. The results are shown in Table 1.

Table 1. HIGH DRIVE PRESSURE RUNS

Run No.	Drive Pressure (psig)	Throat Velocity (fps)	Cavitation Pressure (psia)	Thru-Flow at Inception (per cent)
33	7.93	90	-32	60
34	9.05	81	-20	54
35	8.99	93	-35	72
37	9.0	64	-4	16
38	9.21	82	-21	45
39	9.15	76	-15	21
40	9.10	79	-18	28
41	9.15	95	-36	68
42	8.54	92	-34	39

Table 2 is a series of runs with unpressurized samples. Note that only one of the seven tests of unpressurized samples showed any tension. The average pressure at which cavitation appeared for all seven runs was 0.93 psia. The average water temperature was 75°, which corresponds to a vapor pressure of 0.43 psia. This indicates that cavitation occurred at approximately 0.5 psi above vapor pressure. However, the pressure in the working section is calculated on the assumption of uniform velocity across the cross section. This tends to give too high an estimate of the pressure in the throat because even at these velocities along a smooth glass nozzle, there is a small boundary layer effect. Thus, it must be concluded that under the conditions of this test, the unpressurized water cavitates when vapor pressure is reached.

Table 2. LOW PRESSURE DRIVE RUNS

Run No.	Drive Pressure (psig)	Throat Velocity (fps)	Cavitation Pressure (psia)	Thru-Flow at Inception (per cent)
14	4.71	51	1.33	21
15	4.22	51	1.43	25
16	3.55	50	1.20	30
17	2.98	49	0.99	50
22	4.27	51	1.24	30
23	3.83	52	0.24	35
24	3.69	52	-0.19	40

Values given in Table 1 of pressure and velocity used in testing the pressurized samples represent the conditions at the appearance of the first cavitation bubble. It should not be inferred from this that all of the portion of the sample passing through the venturi throat before cavitation took place was tested at an equally high tension. Figure 11 is a plot of the pressure in the venturi throat as a function of the percentage of the sample which has passed through the throat. This is plotted for Run No. 41 but is substantially correct for all other runs using the 9 psig drive pressure. However, this validity extends only to the point at which the cavitation first appears. At this instant, the effective flow resistance has a discontinuity, since the throat pressure suddenly jumps from the negative value indicated to vapor pressure. Stated in words, the meaning of Run No. 41 is about as follows: the total pressurized volume of the sample upstream from the throat is approximately 850 cc. At the beginning of the test the flow was accelerated during the time required for the first 400 cc to flow through the throat. Of this the first 60 cc passed through before the throat pressure had dropped to vapor pressure. The remaining 340 cc were subjected to tensions varying from zero to 40 psi. During the passage of the next 200 cc the velocity and pressure remained about constant, the latter being 40 psi tension. The throat velocity corresponding to the 40 psi tension is 94 1/2 fps. Flow conditions during the passage of the final 250 cc were indeterminate since, with the beginning of cavitation, both the velocity and pressure fluctuated. However, the photographic

records used to determine the velocity show that in the throat section there was an average velocity corresponding to a tension of approximately 25 to 30 psi. After the first cavity formed there was undoubtedly a series of relatively high magnitude pressure surges imposed upon the flow. Nevertheless, only two or three new cavities formed in the throat. Since the length of the throat section is 3/4 in., it takes an element of water somewhat less than 0.0007 sec to pass through it. That is, each element is subjected to the maximum tension for approximately 0.001 sec.

This verbal description of the way that the test conditions vary during one run demonstrates the need of analyzing the significance of these results very carefully before venturing to make any comparison with the boiling point tests. Thus, for example, the selection of a given drive pressure-difference determines the maximum tension to which the liquid will be subjected. Only the fraction of the total sample that passes through the throat after the equilibrium velocity has been reached is stressed to this maximum value. This test does not determine the tensile strength of any element of fluid. It can only be concluded that those elements which pass through without rupture have a tensile strength above the test value, whereas the tensile strength of those elements in which cavities are produced was below the test value. The amount of liquid involved in one run on the venturi is much larger than that used in the boiling point tests. The initial volume of the liquid above the working section is about 30 times that of the boiling point tube. In Run No. 41 the equivalent of seven boiling point samples were subjected to the maximum tension without failure.

Figure 12 shows the portion of the photographic record of Run No. 41 during which the first cavity was formed. It is quite obvious that this cavity developed in the body of the flow. For example, its average velocity can be estimated from the distance traveled in the .001 sec. between the first two frames in which it is visible. This was 94 fps, which, within the limits of accuracy of these measurements, is the same as the velocity of the flow. Records from other runs show that cavities also develop on the venturi wall. In this case, however, the cavity is fixed. Occasionally, this type of cavity persists until the end of the run, but usually it collapses completely after a comparatively short life, possibly at the end of the first filling cycle.

The glass venturi tubes used in this experiment have relatively thick walls in the diffuser section, which in general are strong enough to withstand the shock pressures developed at collapse. However, Fig. 13 is a portion of the record from Run No. 43, which shows the breaking of a tube coincident with a cavity collapse, thus proving conclusively the existence of high shock pressures.

Comparison of Results

The maximum tensions observed in the venturi tube tests are about one order of magnitude lower than those obtained in the boiling point and pressure chamber investigations. Since the original objective of the venturi test was to see whether or not flowing liquid could withstand the high tensions observed under static conditions, it would appear that these tests showed that they could not. However, closer examination indicates that the difference in the test values may be inherent in the method of testing rather than attributable to the fact that the liquid is moving. In the first place, it would appear that the chief characteristic difference between moving liquids and stationary ones which might tend to decrease the effective tensile strength, would be turbulent motion. Unfortunately, turbulence in the venturi test section, if any, will be confined to the boundary layer and the liquid immediately adjacent to it. The monotonic design of nozzle shape which is required to obviate the possibility of cavitation upstream from the throat insures smooth acceleration with no random pressure disturbances. There is, of course, a symmetrical shear pattern due to the changing cross section, but with this exception: the turbulence must develop at the boundary and work towards the center. However, the length of flow path is too short to permit the turbulence to spread across the cross section until well into the diffuser. In the nozzle and working section the boundary layer must be very thin. The motion picture records show that when cavities do form they travel in a straight line and most of the cavities that are seen are in the main body of the flow and move with the full velocity of the flow. All of these facts indicate little or no turbulent motion in the main flow passing through the working section. Hence, there seems to be little reason to anticipate that the liquid in the venturi tube tests would show lower tensile strength than that in the other types of testing. In fact, the reverse might be expected, since the liquid in the venturi tubes is tested at room

temperature in contrast to the high temperatures of the other two test techniques. Figure 14 is reproduced from Briggs.[11] It will be seen that the experimentally determined effective tensile strength of water is a maximum near room temperature and decreases to approximately 30 per cent of this value at the highest temperatures reached in the boiling point tests.

If the characteristics of the different methods of testing are now examined, it will be seen that in both the pressure chamber and the boiling point experiments the entire sample is tested simultaneously. If it does not fail at a given tension, this is increased until failure does occur. In the venturi tests a certain maximum tension is obtained at the end of the acceleration period, after which the tension remains relatively constant while a large volume of test liquid is forced through the working section. Each element of liquid is tested only once. Table 1 shows that on the average many times the volume of liquid used in the boiling point tests passed through the working section in the venturi tests before failure occurred. Thus the effective tensile stress at failure in the venturi tests is more nearly comparable to the minimum tensile strength obtained in a group of boiling point tests in which the aggregate volume of samples tested is comparable to that tested in one venturi run. In the boiling point tests it was common practice to clean, fill, pressurize, and test groups of six samples. Table 3 shows the maximum, average, and minimum tensile strengths observed in a series of such groups of six.

It will be seen that the average of the minima of the boiling point samples is less than twice the average of the nine venturi runs. This is reasonable agreement, especially when it is remembered that it was impossible to use as meticulous a cleaning technique with the venturis as with the capillary top test tubes. Thus it must be concluded that these experiments show no significant difference between the tensile strength of flowing liquids and stationary ones.

Table 3. TESTS OF TENSILE STRENGTH OF PRESSURIZED SAMPLES PREPARED AND TESTED IN GROUPS OF SIX

Group No.	Cavitation Temperature				Effective Tension		
	Date	Min.	Max.	Ave.	Min.	Max.	Ave.
1	4/28/50	342	386	364	106.8	195.8	146.5
2	4/28/50	284	374	352	38.0	167.7	123.8
3	5/3/50	284	390	358	38.0	206.0	134.8
4	5/12/50	305	377	339	57.8	174.4	100.0
5	6/1/50	317	428	370	71.5	322.2	159.0
6	6/1/50	302	361	328	54.6	140.6	85.8
7	3/28/52	265	288	277	24.2	41.4	32.5
8	3/31/52	235	306	279	8.4	58.9	34.0
9	4/2/52	226	302	282	4.9	54.6	36.3
10	4/4/52	300	360	333	52.6	138.6	83.0
11	4/7/52	293	346	322	45.9	113.4	77.8
12	4/8/52	286	440	352	39.7	36.72	123.8
13	4/14/52	296	326	313	49	83	66.8
Over-all Average		287	360	328.5	45.5	159.0	92.7

The experimental measurements which form the basis of Briggs' curve, (Fig. 14) were all made with purified water, and great care was exercised to remove all of the dissolved gas before testing. This is also true of nearly all similar work up to the experiments of Harvey and his group. Thus, it is rather surprising to see how close the pressure chamber and the boiling point experiments approached Briggs' curve in light of the fact that the water used in the present experiments was saturated with air at atmospheric temperatures and contained relatively high amounts of dissolved salts and also the normal complements of dust particles and other undissolved impurities. On the other hand, the large scatter between the results of the individual experiments implies that there must be a wide range in the resistance of individual nuclei to pressurization. Since none of these higher temperature experiments reached the maximum values shown by Briggs, it must be concluded that the pressure treatment was

never successful in eliminating all nuclei. Since none of the venturi tube tests even approached the order of magnitude of the tensile strengths obtained by Briggs in his centrifuge tests, these results also imply that the concentration of pressure resistant nuclei is relatively high. Hence, even if all of the water in a water tunnel circuit could be pressurized, there would still be many weak spots remaining whose tensile strength would not exceed a few pounds per square inch. Consequently, although there might be definite indication of hysteresis in the cavitation inception point, the average cavitation performance would not differ widely from that obtained with unpressurized water.

Another explanation of wide scatter was suggested by Briggs. His basic concept is that a liquid which is being tested for tensile strength is essentially a "bubble chamber" and thus sensitive to radiation, especially to cosmic rays and that due to radioactive contamination such as is present in the walls of concrete buildings, etc. For example, the average intensity of radiation from all sources in the concrete buildings at the California Institute of Technology seems to be about 10 per sec per cu. cm, of which about 20 per cent is due to cosmic rays. It is obvious that the possible effects of radiation in initiating cavities will be quite different for the three approaches used in this investigation, i.e., the boiling point experiments, the pressure release experiments, and the venturi runs. In the first two the same sample container was adopted as standard, i.e., the 18 mm test tube which holds approximately 30 cc. Thus an average of 300 rays per second must pass through the sample during the testing period. However, the only rays which might possibly initiate premature cavitation are those which pass through the sample while the latter is superheated. When the boiling point tests are examined from this point of view, it is seen that this period is relatively long. The variation in results is strikingly illustrated by the performance of a single batch of six samples which was tested during the latter part of the program after the technique had been perfected. They were tested consecutively during a single afternoon. An initial period of about two minutes was required to heat each sample from room temperature to 211°. From this point on the liquid was superheated, and therefore in a condition in which a triggering effect of a penetrating ray

might initiate a cavity. The next to last sample gave the lowest boiling temperature and the last one the highest. The lowest one was superheated for 68 sec before it failed; the highest one for 272 sec. Thus, the high boiling point sample was heated above the failure temperature of the preceding test for over 200 seconds, during which time approximately 60,000 local and cosmic rays must have passed through it without initiating a cavity. These results have two possible explanations: either the radiation must have a tremendously wide variation in energy level, of which only the highest are effective in inducing nucleation in the superheated samples, or that radiation is ineffective in producing nuclei in superheated water. The second explanation implies that the boiling point was determined by the largest effective nucleus remaining in the sample after the pressurizing treatment, and that this size was very different for the two samples.

Consider next the pressure release tests. Here the sample size is the same and hence the number of individual rays passing through the sample per second is the same. However, the time that the sample is in a superheated condition in this test is very different from that of the heating tests. In the pressure chamber most of the heat received by the sample was from the surrounding vapor. Hence, during the heating period the sample always was at a pressure slightly above the vapor pressure. During the test the pressure was released at approximately 30 pounds per sec. Thus the sample which withstood the highest effective tension was under superheat conditions for only about 15 sec. In other words, the testing time in the pressure chamber is an order of magnitude lower than that in the heating coil tests. The fact that the effective tensions obtained in the pressure chamber were somewhat above those obtained in the heating coil tests might be explained on the basis of the shorter exposure to radiation while superheated. On the other hand, in the discussion of the pressure chamber tests, it was pointed out that there was evidence that the self-pressurizing effect in this test produced a general increase in the effective tensions measured.

The conditions during the venturi tests were quite different. Although the volume of the sample was very large, the fraction of it that was ex-

posed to radiation while under tension was very small. It is estimated that the volume of the throat section in which tension exists is approximately 10 cc. The maximum time during which tension existed in this section before cavitation occurred was 0.1 sec., and the average time before failure was approximately one-half of this. Thus for these tests the maximum number of rays which might have caused nucleation was approximately 10. When this is compared with the figures of 6,000 for the pressure chamber and 60,000 for the boiling point tests, it would appear that radiation could have had little effect on the venturi tests. Since these venturi test results have the same wide scatter as those of the other two tests, and since the tendency is, if anything, to indicate a lower effective tensile strength, this lack of effectiveness of radiation in the venturi tests implies that radiation is not the primary cause of high scatter in these investigations.

The most plausible remaining explanation is that cavitation is initiated by the largest effective nucleus remaining in the liquid after the pressurizing treatment.

Characteristics of Nuclei. The results of this program of pressurization tests contains some implications concerning the characteristics of the nuclei.

(1) The effects of pressurization appear permanent as long as the pressurized sample is protected from contamination from the atmosphere. This is shown by the fact that pressurized samples showed high tensile strength after days or even weeks had elapsed between the pressurizing treatment and the testing. This implies that nuclei must have continuing existence, i.e., they cannot be simply transient configurations of the continuously moving molecules of the liquid.

(2) The wide scatter of results shown by groups of samples which have had identical preparation and treatment implies that the individual nuclei must differ widely in their ability to withstand a given level of pressurization. Furthermore, this ability to resist pressurization does not seem to be correlated with their resistance to tension. It is interesting to compare the model of a nucleus proposed by Harvey with that suggested by Fox and Herzfeld[12]. Harvey's model is basically that of a gas bubble located

at the bottom of a reentrant crack in the surface of a hydrophobic particle of solid impurity, e.g., a dust particle. Such a nucleus has two independent properties: a resistance to destruction by the application of high pressure, and an apparent tensile strength, i.e., a specific liquid tension at which a finite cavity will develop from the nucleus. The independence of these two properties may be explained by the simple geometric characteristics of the crack -- the width of the crack at the surface of the particle should control the effective tensile strength: the greater the width, the lower the strength. The resistance to pressurization should be determined by the width of the crack at the bottom. Thus a crack with converging walls which meet sharply without any rounding at the bottom would have an infinite resistance to pressurization; whereas a crack with parallel faces and a rounding bottom would have a pressure resistance of the same order as the effective tensile strength. If the angle of convergence of the crack walls remains constant, there would be a definite relationship between the depth of penetration of the liquid in the crack, the ambient pressure of the liquid, and the concentration of the gas dissolved in the liquid, i.e., a given ambient pressure and degree of saturation of the liquid would correspond to a given size of nucleus. If the ambient pressure of the liquid is raised, it will penetrate deeper into the crack, forcing a portion of the gas in the pocket to dissolve. This will continue until the radius of curvature of the convex surface of the penetrating liquid has decreased until the surface tension forces are again in equilibrium with the new pressure level. If the pressure is now reduced to the original value, the nucleus should grow back to its original size at a speed which would be determined by the rate of diffusion of the dissolved gas in the liquid through the interface. Thus, unless the pressurization is high enough to destroy the nucleus by causing all of the gas to dissolve, it should have no effect upon the effective tensile strength. Cracks having irregular walls, so formed that the crack has the same width at two or more depths, might have their effective strength altered by pressurization. These characteristics of the Harvey nucleus are adequate to explain, without inconsistencies, the experimental results of this program.

The "organic skin" model of the nucleus proposed by Fox and Herzfeld does not seem to possess the same consistency with the experimental evidence. In their description of this model, Fox and Herzfeld indicate that the organic skin would have a relatively definite crushing strength, of opposite sign but otherwise quite analogous to surface tension forces. Thus the larger the original nucleus the easier it would be to crush during the pressurization treatment, and when crushed, it apparently would not be able to regain its former size because the surface tension forces should be able to hold the diameter of the enclosed gas bubble down to approximately the minimum reached during pressurization. It seems that Fox and Herzfeld's concept of the properties of the molecules of the organic skin is that they are analogous to individual solid plates floating on the interface, as cakes of ice might float on the surface of a lake. Hence, they would have no effect on the surface forces until they touched, due to reduction in the area of the total surface. When they did touch, however, they would be able to resist compression and, assuming that the individual elements are elastic, this would be accompanied by a small deformation. However, if the force causing compression were released, subsequent expansion would only proceed until there was no residual compression between the elements of the skin, i.e., there are no attraction or repulsion forces between the organic skin molecules. Thus the surface tension of the surrounding liquid would be the only force acting to prevent the growth of a cavity from such a nucleus in case the liquid pressure is reduced below the gas pressure in the nucleus. To obtain a rough idea of the characteristics of such nuclei, some elementary calculations were made on the assumption that subsequent to the time that all of the organic molecules touched and formed a supporting shell, the gas initially in the nucleus diffused through this organic skin and dissolved in the liquid, leaving a vapor-filled space. Under these conditions, compression in the organic skin would be the sole resistance to the surface tension forces acting to collapse the nucleus. Such nuclei would start to grow when the liquid is subjected to an effective tension just sufficient to overbalance the surface tension forces. On this basis nuclei sizes were calculated corresponding to effective liquid tensile strengths of from 0.1 to 100 atmospheres; next,

the crushing strength of the organic film required to enable nuclei of these radii to resist a pressurization of 1000 atmospheres was computed. The results are shown in Table 4. It will be noted that these crushing strengths appear as powers of ten multiplied by the surface tension. Present knowledge of the physical properties of such organic skin indicates that they may have crushing strengths about equal to the surface tension of water, or possibly slightly higher. Table 4 shows that crush-

Table 4. REQUIRED PROPERTIES OF "ORGANIC SKIN" NUCLEI

Effective Tensile Strength of Liquid (Atmospheres)	Radius of Nucleus (cm)	Pressurization (Atmospheres)	Required Crushing Strength of Organic Skin (Dynes/cm)
0.1	1.4×10^{-3}	1000	70×10^{4}
1	1.4×10^{-4}	1000	70×10^{3}
10	1.4×10^{-5}	1000	70×10^{2}
100	1.4×10^{-6}	1000	70×10

ing strengths of this magnitude are not sufficient. For example, if a liquid containing organic skin nuclei began to develop cavities at an effective liquid tension of 10 atmospheres after being previously pressurized to 1000 atmospheres, the organic skin would have had a crushing strength of 70×10^{2}. This is 100 times greater than the probable strength of such skins. The development of a cavity at only one atmosphere tension after the same pressurization would increase the required film crushing strength by a factor of ten. Furthermore, to explain the wide scatter of the results observed in these experiments would require a chance variation in the film strength of approximately 100:1. This also appears highly improbable. It should be noted that another difficulty is encountered if this model of the nucleus is used to explain the experimental results. Cavitation at a low tensile stress in the liquid after the standard pressure treatment requires a very high strength organic film, which, if it ever exists, would occur very infrequently. However, the tests showed that cavitation occurred often at low effective liquid tensions.

The foregoing attempts to explain the experimental results of this program on the basis first, of the Harvey model of the nucleus, and second, on that of Fox and Herzfeld, seem to furnish a sound comparison of the relative acceptability of these two models. The observed experimental results are all explainable by the Harvey nucleus. Furthermore, these explanations do not require any improbable variations in the physical properties of the quantities involved. On the other hand, serious difficulties were encountered in using the Fox and Herzfeld model. These difficulties could be overcome only by assuming improbable characteristics for the organic skin. It must be concluded, therefore, that the Harvey model is still the best tool available for use in the analysis of cavitation phenomenon.

SUMMARY OF RESULTS AND CONCLUSIONS OF EFFECTS OF PRESSURIZATION

(1) The effective tensile strength of water is increased by pressurizing it before subjecting it to tension. The amount of this increase varies with the level of pressurization, but the inherent scatter in the results makes it difficult to detect any significant increase above a pressurization level of 200 to 300 atmospheres. Although no specific experiments were made to determine the lower limit of pressurization which would produce a significant increase in tensile strength, such effects were observed at pressurization levels of 20 to 30 atmospheres.

(2) Pressure-resistant weak spots often occur on solid surfaces. Such weak spots initiate cavity formation in both still and flowing liquid. The fact that on glass surfaces they normally can be removed by vigorous cleaning methods implies that these weak spots are due to contamination with hydrophobic impurities.

(3) No correlation was found between the increase in effective tensile strength and the duration of the pressurization, within the limits of the experimental equipment. The shortest treatment time was approximately one minute, i.e., the minimum time required to apply and remove the pressure. The longest was several days.

(4) The effect of pressurization lasts at least for weeks, provided that precautions are taken to prevent contamination with foreign nuclei. This fact is not compatible with the concept that nuclei are chance "holes" in the liquid, formed by the random motion of the molecules in accordance with statistical distribution laws.

(5) The initial purity of the water is not a significant factor. No quantitative tests were made with samples containing large volumes of soluble gases, but there was no detectable difference in behavior between multiple-distilled water and air-saturated tap water containing relatively high concentrations of dissolved and suspended material. No measurements were made with mote-free water.

(6) No correlation was found between the average tensile strength at failure and the duration of the tension even though this duration varied over several orders of magnitude between the different tests. This result implies that cavity formation in liquids under tension cannot be explained by nucleation resulting from cosmic rays or other high energy radiation received by the liquid while under tension.

(7) By a process of elimination, the results of these experiments point to the existence of a real nucleus which has a continuing existence and certain specific properties.

(8) The physical concept or "model" of the nucleus which is most compatible with the results of this program is that of Harvey, i.e., a gas pocket in a reentrant crack in the hydrophobic surface of a solid particle.

(9) The concentration of highly pressure-resistant nuclei in natural water seems to be relatively low. For example, these tests imply concentrations of the order of one nucleus to 30 cc whose effective tensile strength is approximately 15 atmospheres and whose resistance to pressurization exceeds one thousand atmospheres, and one nucleus to two hundred cc whose effective tensile strength is one atmosphere, and whose pressure resistance is at least 1,000 atmospheres.

II. Mechanics of Fixed Cavitation

The study of the mechanics of fixed cavitation is one phase of an investigation of the mechanics of the cavitation process which has been under way for some years. A general summary of this work is contained in the paper entitled, "Cavitation Mechanics and Its Relation to the Design of Hydraulic Equipment", by Robert T. Knapp, which was presented as the James Clayton Lecture to the Institution of Mechanical Engineers in 1952. In this previous work it had become clear that there are two common types of cavitation: (a) traveling cavitation, in which the individual cavities formed and moved with the average velocity of flow, and (b) fixed cavities, i.e., relatively large voids bounded on one side by the guiding surface and on the opposite side by the free surface of the flowing liquid. The mechanics of traveling cavities having been studied in considerable detail, attention was fixed on a similar study of the mechanics of the fixed cavities. The results were first presented in a report, "Recent Investigations of the Mechanics of Cavitation and Cavitation Damage", in London, England, September 1954. Since this was a closed conference, substantially the same material was presented under the same title at the annual meeting of the American Society of Mechanical Engineers, November 1954.[+] Basically this investigation was experimental. It was carried on in the High-Speed Water Tunnel, using two and three-dimensional simple geometric shapes. The dynamics of the fixed cavity was studied through the use of high-speed motion pictures, taken at rates of from 3,000 to 20,000 per second. It was found that a cyclic process is involved in fixed cavitation, consisting of development, filling, and breakoff. The phenomenon responsible for the cyclic character is the reentrant flow which enters the cavity from the downstream end, as required by conservation of momentum. This process has some similarity with that of the Karman vortex street, but the factors determining the duration are quite different. Thus, a range of frequencies are possible for a constant velocity of flow over the same guiding surface. Here the added variable is the length of the cavity. Since the details of this study are available in the references cited, no further description will be given.

[+] Awarded Melville Medal for 1954, American Society of Mechanical Engineers.

III. Mechanics of Cavitation Damage

Strictly speaking, the scope of this investigation was somewhat more limited than the title implies. It might be more properly called, "Hydromechanics of Cavitation Damage Resulting from the Action of Fixed Type Cavitation". This was an extension of the work of Part II, and since it involved the same equipment and technique, the experiments also yielded additional information concerning the mechanics of the cavitation process. A careful study of the photographic records obtained in Part II showed that the free surface of the fixed cavity was covered with small traveling cavities which disappeared at the end of the fixed cavity, the majority of them apparently being swept upstream into the cavity by the reentrant flow. These small cavities seemed to furnish a clue as to a possible mechanism through which the fixed type cavity could cause damage, i.e., through their collapse in or near the stagnation zone at the downstream end of the fixed cavity. One major addition was made to the previously used experimental technique. The guiding surface in the cavitation area and immediately downstream from it was made of annealed pure aluminum of standardized hardness. This aluminum was used to record the individual mechanical blows struck by the collapsing cavities. It was found that these blows produced symmetrical round pits or craters, with small raised rims, quite typical of the plastic flow produced by indentation of a metallic surface with a spherical ball. Counting techniques, using low-power photo-micrographs, were developed for determining the pitting rate corresponding to various cavity lengths and flow velocities.

The major results from these studies were:

(a) For a given flow velocity over a given guiding surface, the pitting rate per unit width of surface is independent of the length of cavity. This is not true for the extremely short cavities characteristic of inception conditions, nor is it valid if the maximum length of the cavity is greater than that of the guiding surface;

(b) A corollary to the above statement is that the pitting rate per unit area decreases as the cavity length increases;

(c) For otherwise similar conditions, the pitting rate varies with some high power of the flow velocity. Indications are that this variation is with the sixth to eighth power of the velocity.

(d) The size range of the pits on the standardized material seems to vary very little with the size of the guiding surface, i.e., it appears to be primarily a function of the properties of the liquid;

(e) There are some preliminary indications that the pitting rate is affected by the initial thickness of the reentrant flow into the fixed cavities;

(f) The pitting rate is independent of time. This suggests the usefulness of the pitting rate as determined by direct observation on a standardized material as a quantitative measure of the cavitation intensity.

The results of this portion of the project have been reported in the following articles:

Recent Investigations of the Mechanics of Cavitation and Cavitation Damage. Presented at 1954 Joint Admiralty-U.S. Navy Meeting, in London, England, September 1954.

Recent Investigations of the Mechanics of Cavitation and Cavitation Damage. Presented at ASME annual meeting. Nov. 28-Dec. 3, 1954. Published in Transactions, ASME, Vol. 77, No. 7, October 1955, pp. 1045-54.

Further Studies of the Mechanics and Damage Potential of Fixed Type Cavities. Presented at Symposium on Cavitation in Hydrodynamics, National Physical Laboratory, Teddington, England, September 14-17, 1955.

IV. Field Tests of Intensity of Cavitation

This phase of the investigation was not contemplated in the original contract nor in its extensions. It was suggested by the results of Part III, particularly by the success of the technique of utilizing annealed aluminum plates to determine the intensity of the cavitation damage attack. Since little had been known previously about the intensity of this attack, and still less of relative intensities between laboratory conditions using small-scale equipment and the field operation of large machines, it appeared to the Official Investigator that if this technique could be employed in field equipment such as large turbines, it would be possible to get some quantitative information bearing on these very important questions. After some discussion, the ONR agreed that a limited amount of time of the technical staff of the project could be spent on such an investigation, but did not authorize travel or other required expenses. Hence, additional sponsorship was obtained from other sources, primarily the Bureau of Reclamation and the Metropolitan Water District of Southern California. Arrangements were made to carry out the tests in one of the Francis turbine units at Parker Dam on the Colorado River. Test plates were installed on the leading edges of two vanes of the turbine, covering areas which were known to suffer from cavitation under full-load operating conditions. A series of successful runs was made and the test plates evaluated. The results were very promising, and yielded the following conclusions:

(1) By means of relatively simple techniques, test plates can be installed in existing equipment requiring relatively little shutdown time for the purpose;

(2) Only very short runs are needed to determine the pitting rate. Under the conditions existing at Parker Dam, runs of from five to twenty minute duration were sufficient;

(3) The pitting rates obtained were in good agreement with those measured at the same velocities in the water tunnel. Although these tests are preliminary in nature only, and supply insufficient

evidence on which to base final conclusions, they do point to the probability that there is not a large scale factor involved in the intensity of the cavitation damage attack.

The techniques employed and the results of these tests are described in a paper presented at the 1956 annual meeting of the American Society of Mechanical Engineers, entitled "Accelerated Field Tests of Cavitation Intensity", and scheduled for publication in 1957.

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4. "Bubble Formation in Animals," by E. Newton Harvey, D.K. Barnes, W.C. McElroy, A.H. Whiteley, D.C. Pease, and K. W. Cooper, Jl. of Cellular and Comparative Physiology, vol. 24, 1944, pp. 23-44.

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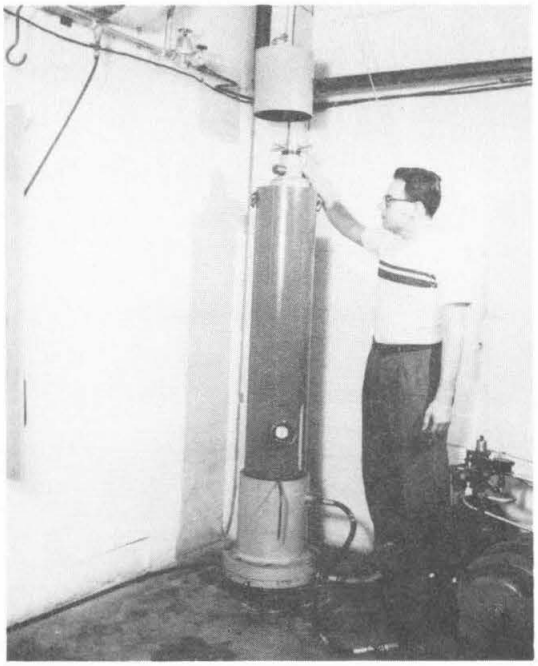

Fig. 1 - Pressurizing Chamber

Fig. 2 - Complete Pressurizing System

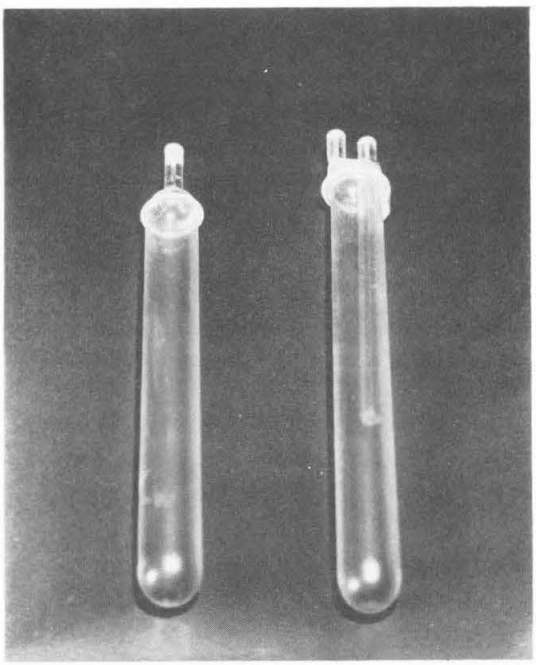

Fig. 3 - Single and Double Capillary Closed Top Test Tubes

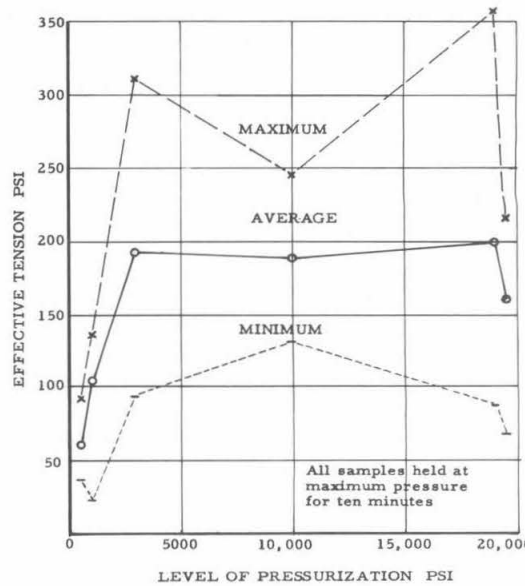

Fig. 4 - Effect of Level of Pressurization on Boiling Point Tests

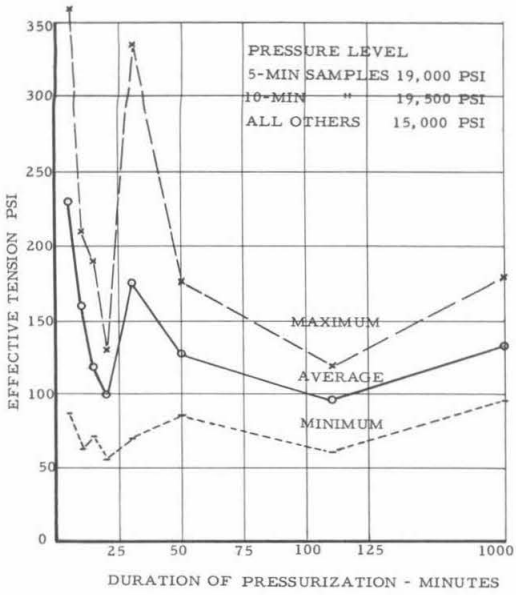

Fig. 5 - Effect of Duration of Pressurization on Boiling Point Tests

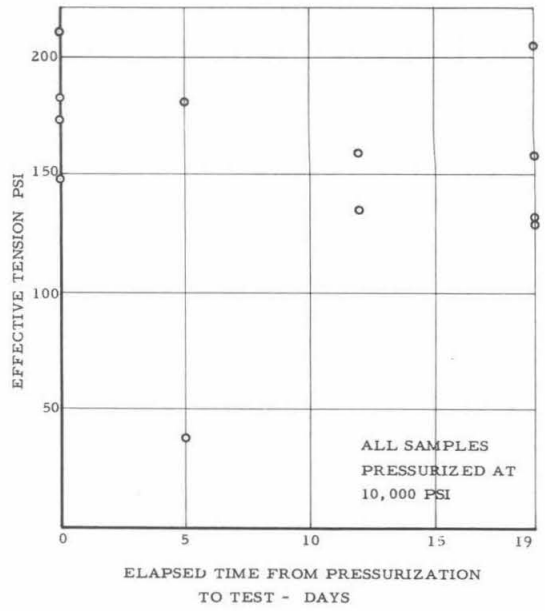

Fig. 6 - Effect of Time Interval between Pressurization and Test on Boiling Point Tests

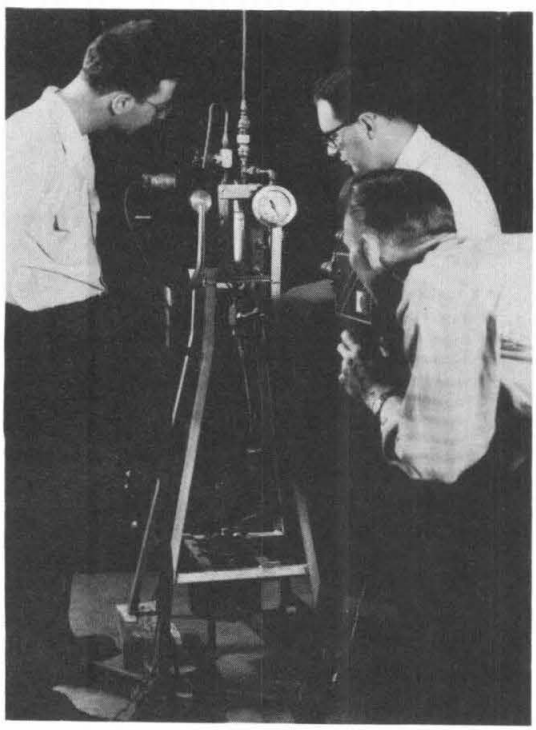

Fig. 7 - Pressure Release Chamber

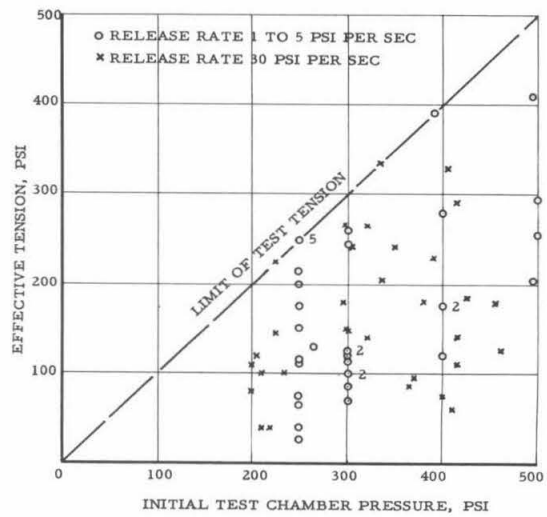

Fig. 8 - Summary of Test Results from Pressure Release Chamber

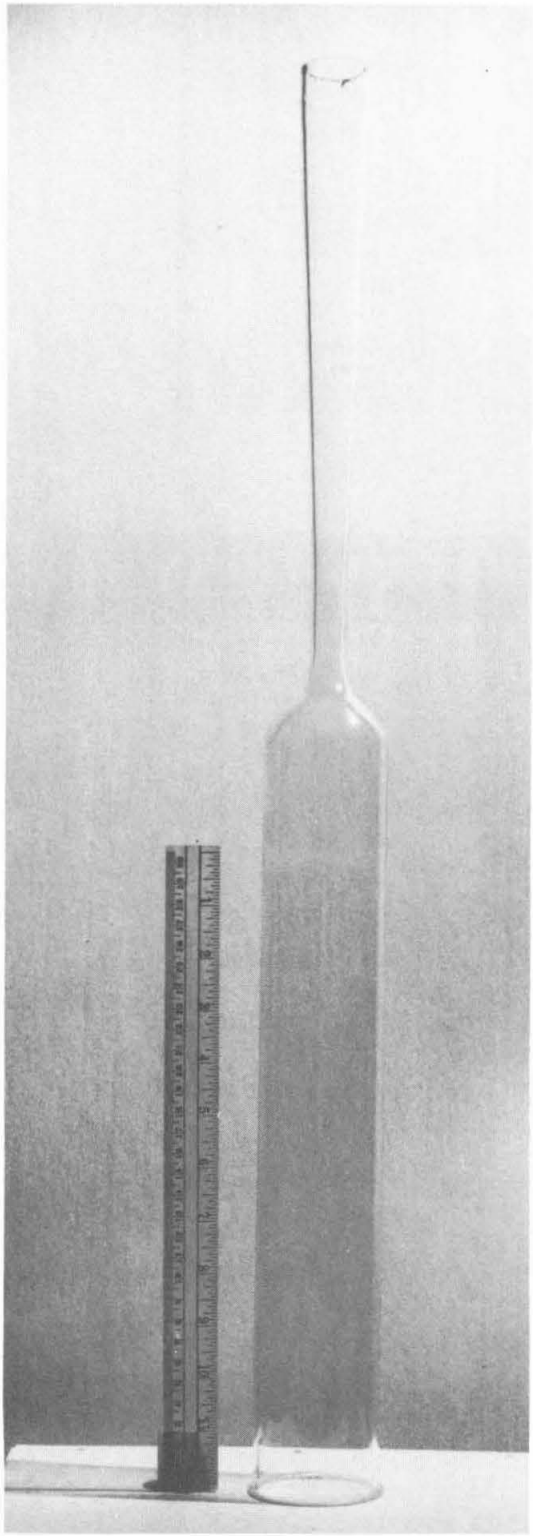

Fig. 9 - Glass Venturi Tube

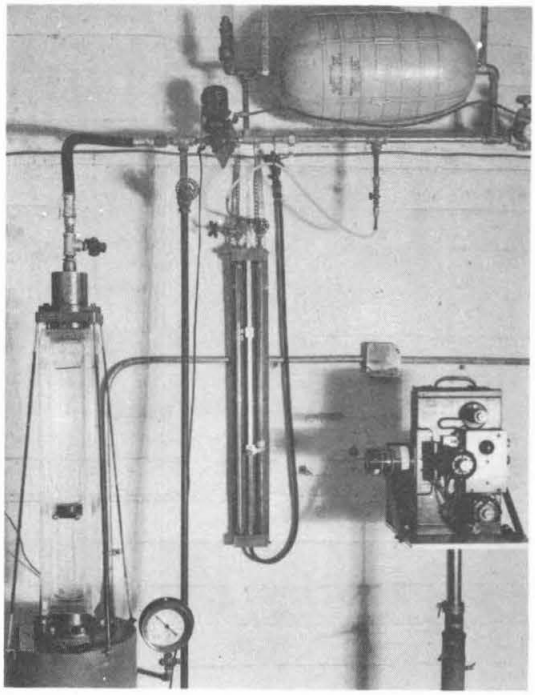

Fig. 10- Venturi Tube Test System

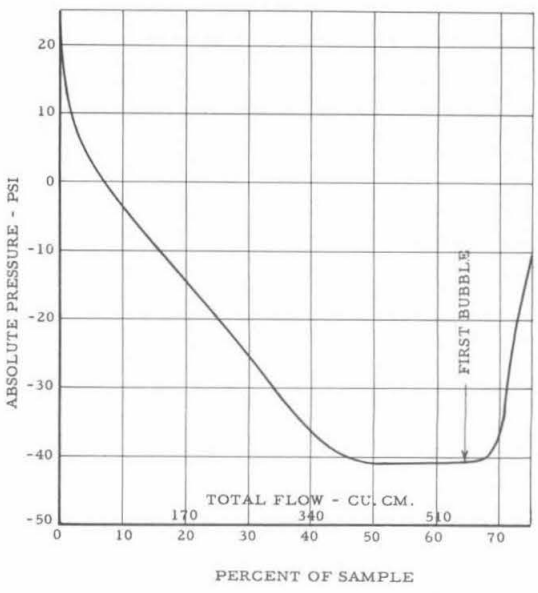

Fig. 11- Typical Pressure Variation During Venturi Tube Test - Run No. 41

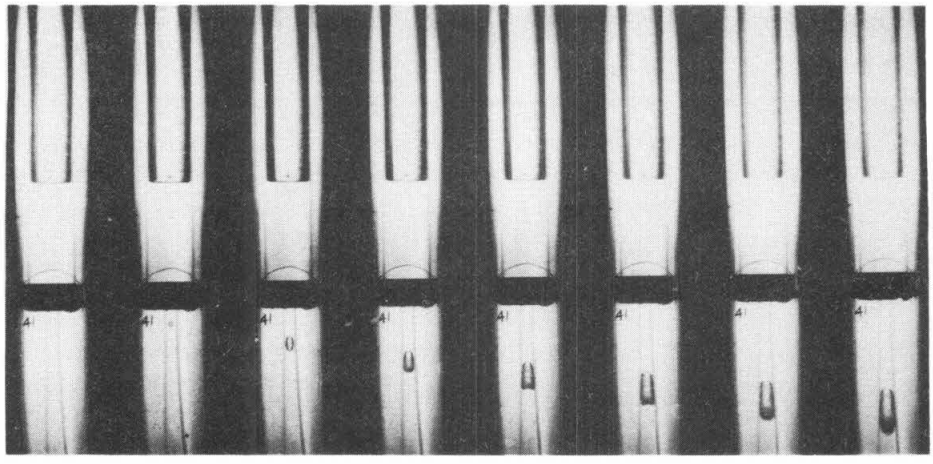

Fig. 12- Formation of First Bubble During Run No. 41

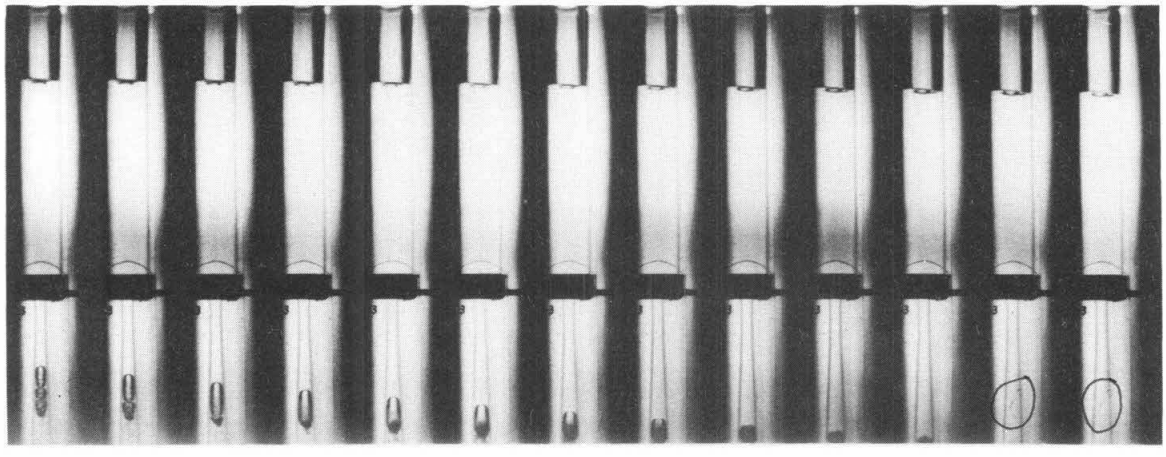

Fig. 13- Breaking of Tube During Cavity Collapse - Run No. 43

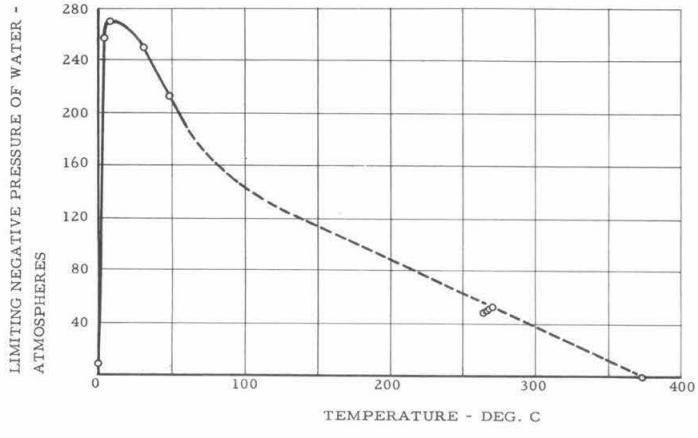

Fig. 14- Variation of Limiting Negative Pressure of Water with Temperature. (Fig. 1 of Ref. 11)

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